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Use of Operational Models
In Considering
Implementation Strategies For
Combined Use of Two- and One-Officer Cars

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1 INTRODUCTION

One- versus two-officer cars? This has remained one of the most controversial questions facing police administrators for the past fifty years. The question is often posed in an "either/or" fashion which masks the myriad possibilities for combining both one- and two-officer cars in a mutually supportive operating environment. In a recently completed survey of 231 large city and county police departments in the U.S. [1], PSE discovered that fully 97.5 percent of responding departments use a combination of one- and two-officer police cars. Such police departments often utilize one or more of the following operational procedures:

- Use of two-officer cars primarily for high priority calls for service from the public (e.g., felony in progress, "officer in trouble"), and simultaneous use of one-officer cars for lower priority calls for service.

- Encouraging officers in one-officer cars to become more familiar with the community in which they patrol, and designing the police response system so that these cars do not leave their home precincts and so that they have a larger than average fraction of time available for preventive patrol.

- Using more one-officer cars during daylight hours and a higher proportion of two-officer cars at night.

- Requiring simultaneous dispatch of both a two-officer car and a one-officer car for certain types of incidents.

- "Workload shedding" of routine activities from two-officer cars to one-officer cars.

- Expanding the response territory of two-officer "rapid response" cars in order to alleviate queueing type congestion (i.e., delay) at the dispatcher's position due to too few cars servicing a given territory.

PSE's national survey revealed that all of the above ideas (and more) are used in various combinations in police departments throughout the United States.

Yet the way in which a given department relates its own particular combination of operating procedures is often a trial and error proposition, based on intuition, responses from patrol officer's labor bargaining unit, responses from citizen's groups, or budgetary constraints imposed by "City Hall". Our contention is that the almost limitless number of combinations of operating policies involving one- and two-officer units require a systematic and often quantitative procedure to evaluate the consequences of each proposal <u>prior</u> to implementation. Since a police emergency response system is a complex logistical system operating in an uncertain (i.e., probabilistic) environment, it has its own "laws of physics" that must be derived and understood in the operations design process. Such an environment is ideal for the development and application of mathematical models of police patrol (and dispatch) operation. A diverse and rich set of models have been developed over the past 15 years or so [2], and much additional work remains to be done as police departments discover yet new ways to operate that here-to-fore have not been modeled.

For this paper, it is our purpose not to develop new models, but to illustrate the use of models (one new and one old) in a new setting -- the compatible use of one- and two-officer cars. We had hoped to be able to illustrate the use of the models discussed in an actual police management/labor negotiations process in a major U.S. city. Unfortunately, the scheduled negotiations have been delayed beyond the research grant termination date, and thus we are faced to rely on hypothetical illustrations.

By the use of the models discussed herein, we hope to achieve the following objectives:

- Demonstrate the decision and planning benefits of using models of proposed operations prior to implementation.

- Illustrate the types of operational procedures that must be considered when staffing both one- and two-officer cars for the same service area.

- Illustrate how a model in the public domain can be useful in the detailed analysis of one- and two-officer car operation.

- Illustrate the types of new performance measures that are necessary for considering merged one- and two-officer car operations.

In Section 2 we apply a new aggregate model of "mixed-mode" operations toward a set of planning questions analogous to those asked of the "PCAM" [3] model in non-mixed-mode operations. This new model was developed specifically for New York City, whose police department considered the use of mixed-mode patrol (in contrast to nearly all two-officer patrol) in 1981-82. In Section 3 we apply the Hypercube Model (which has been in the public domain since 1975) to detailed operational (e.g., dispatch and beat assignment) issues involving mixed-mode patrol. Further mathematical details are found in the cited references.

2 CASE STUDY: AGGREGATE MODELS

The purpose of this Section is to illustrate how aggregate police patrol models can be used to aid city and police planners in implementing alternative patrol car deployment strategies. As discussed in Section 1 of this report, in the absense of actual field tests, such models can be extremely useful, since often the consequences of altering operating procedures are too complex to track mentally. Fortunately, aggregate models exist that are not only mathematically tractable, but also yield results sufficiently accurate for policy and decision making purposes. Many patrol-related models — and, in particular, the model described in this section — are based on queueing theory, the branch of operations research which explores the relationship between demands on a service system (e.g., a police emergency response system) and the delays suffered by users of the system. Such models assume that calls for service arrive at a police communications or dispatcher center and are subsequently assigned to an available patrol car, or, if there are none available, delayed in the dispatcher's queue and assigned when a unit becomes free. The models are "aggregate" in the sense that they assume all servers (i.e., patrol cars) in a particular queueing system are indistinguishable in terms of workload, service time and other patrol characteristics. (In Section 3, disaggregate models, that do include the individual characteristics of each patrol car, are discussed and applied).

Returning to the issue of one- versus two-officer car deployment, it is clear that a planner could design a model that assumes all two-officer cars are used, or a model that assumes all one-officer cars are used. Based on the respective model-computed performance measures, the planner could compare the performance of the two different deployment strategies. This type of comparison is well-documented in a paper by Kaplan, "Evaluating the Effectiveness of One-Officer Versus Two-Officer Patrol Units." [4] In view of this work, our purpose here is to illustrate models that allow both one- and two-officer patrol cars. The two types of cars would, ideally, be used in a mutually supportive and compatible way.

What are the advantages of using a combination of one- and two-officer units? If the department has primarily used two-officer cars, a change to exclusive use of one-officer cars may be too drastic for the department. Further, it may not be appropriate to use one-officer cars in all areas of a city or at all times of the day, particularly at night. Yet there are real benefits to be gained by using one-officer cars, most of which stem from the fact that for a fixed level of manpower more patrol cars can be fielded. While a more complete discussion of these and other related issues are addressed in a companion report [5] , the bottom line of such a discussion is that there are both compelling reasons for using one-officer cars and equally compelling reasons for using two-officer cars. Thus, a "mixed-mode" deployment strategy (i.e., a strategy using both one- and two-officer patrol cars) is especially appealing; this fact provides motivation to develop models that use both types of units.

2.1 Model Description

The city on which these analyses are based is organized for police purposes into a number of patrol zones, each of which is under the control of one radio dispatcher. Each zone is in turn partitioned into a number of precincts (typically two to four), to which patrol cars are assigned for general patrol and response purposes. At present, all the precincts operate as if they were independent police departments; patrol cars rarely patrol or respond to calls for service outside of their precinct. Also, it should be noted, all patrol cars are currently two-officer cars.

New Operating Characteristics

A number of new operational characteristics are being considered for implementation in the city. They include the following:

- One two-officer car will respond to each high and moderate priority call
- One one-officer car will respond to each low priority call
- One-officer cars will back up two-officer cars on a certain percentage of high and moderate priority calls
- Routine interprecinct dispatching of two-officer cars
- Routine preemption of one-officer cars on low priority calls
- Deliberate workload shedding of two-officer cars

Notice that the two-officer cars will respond exclusively to high priority calls (e.g., crimes in progress). The one-officer cars, on the other hand, will respond to low priority calls, provide backup to two-officer cars on a fraction of high priority calls, and engage in routine preventive patrol. These two operating procedures recognize that it is often wasteful or unnecessary to tie up a two-officer car on, say, the investigation of a past burglary, a call for service that could easily be handled by a one-officer car with little or no risk to the officer. At the same time, the procedures are sensitive to the fact that a high percentage of high priority calls are unfounded, in which case the two-officer car can leave the scene, with the backup one-officer car handling any report taking and other "clean up" activities. This "workload shedding" of two-officer cars is another key new operational characteristic of mixed-mode patrol.

City officials also wish to examine the consequences of redefining the size of the area to which patrol cars can respond to calls for service. While the two-officer cars' primary responsibility in these examples is to respond to high priority calls within their own precinct, it is desired to allow two-officer cars to be dispatched across precinct boundaries into another precinct in the zone. It should be noted, however, that such "interprecinct dispatching" will occur only if all two-officer cars in a precinct are simultaneously busy on other calls for service and a high priority call from the precinct is received. Thus, rather that delaying the call until a two-officer car in that precinct becomes available (which is the current policy), an interprecinct dispatch is performed.

While routine interprecinct dispatching of two-officer cars is to be tested, the question remains as to whether to allow routine interprecinct dispatching of one-officer cars. On the one hand, responding to calls for service in another precinct involves higher risk, inasmuch as the area is less familiar to the officer. The risk to officer safety is, of course, worsened in the case of one-officer cars. Yet, by increasing the "pool" of potential "servers" to calls for service, interprecinct dispatching can improve system performance. In the examples below, however, it is assumed that one-officer cars are not allowed to cross precinct boundaries and therefore will only respond to call for service that originate in their precinct. This policy is motivated in part by the desire to maximize each officer's "precinct identity", that is, to have the officers in one-officer cars establish a sense of responsibility for the community in which he/she patrols.

Finally, the mixed-mode program calls for routine preemption of one-officer cars handling low priority calls when such interruption is warranted to provide initial response backup to a two-officer car being dispatched to a high priority call. Preemption would most likely occur in situations when the one-officer car has been dispatched to a low priority call, but has not yet arrived at the scene.

Fundamental Assumptions

There are several important fundamental assumptions inherent to the mixed-mode model. These assumptions can be stated as follows:

- Calls for service are generated according to the Poisson probability distribution. Each precinct has a different mean call for service rate, a rate which is derived from precinct data.

- Service times of the patrol cars on calls for service are negative exponentially distributed. The mean is, again, precinct-specific and derived from precinct data.

- Patrol cars are always "in-service" (i.e., either assigned to a call for service or available for dispatch assignment). Since in reality patrol cars are often out-of-service — due primarily to meal breaks, car trouble, or administrative details or other precinct assignments — care must be exercised in equating "always in-service, model" patrol cars and "frequently out-of-service, fielded" patrol cars. In all of the illustrative runs in this Section, it is assumed that 1 "model" patrol car equals 1.5 "fielded" patrol cars.

- Average values of call for service rates and service times are constant throughout an eight-hour shift. That is, variations of the rates within the shift are ignored.

- The algorithm for computing travel times assumes that there are no significant barriers to travel in the precinct. Additionally, it is assumed that one of the beat dimensions (e.g., "length") is not much greater that the other beat dimension (e.g., "width").

- All computed performance measures are long-run statistical averages. The mixed-mode model is not a simulation model; in order to obtain values for the various performance measures the model does not consider one by one all of the individual situations that could occur, but instead uses mathematical formulas to compute the average value of each performance measure.

Model Structure

Generic queueing and patrol coverage models were modified to reflect the operating characteristics described above, and are capable of computing the following performance measures:

- Police response time to high priority calls.

- Police travel time to high priority calls.

- Utilization of a patrol unit, measured in fraction of time busy handling calls for service.

- Intensity of preventive patrol, as measured by the frequency of passings of a patrolling unit.

- Fraction of dispatches across precinct boundary lines.

- Fraction of time a unit spends outside of its own precinct.

- Probability that a high priority call will be delayed in the dispatcher's queue due to no two-officer car being available at the time of receipt of the call.

- Probability that a low priority call will be delayed in the dispatcher's queue due to no one-officer cars being available at the time of receipt of the call.

Notice that there are performance measures specific to the two-officer cars (e.g., probability a high priority call is queued, two-officer car workload, fraction of dispatches across precinct boundary lines) as well as those specific to one-officer cars (e.g., probability a low priority call is queued, one-officer car workload). Patrol frequency, on the other hand, reflects the performance of all types of cars.

Another feature of the model is that it is a prescriptive, as opposed to descriptive, model. By that we mean the model informs the planner as to the number of one- and two-officer cars required in each precinct in order to satisfy certain performance objectives. Performance objectives can be specified for any of the model computed performance measures in any of the precincts. The ability to specify a desired performance measure is, again, a useful tool for planners, especially in the context of using both one- and two-officer cars.

The other necessary inputs to the model, such as average call for service rates, the average service time, the area in square miles of each precinct, and the number of street miles in each precinct, all reflect values in the different precincts in the city. Figure 1 identifies the inputs as well as some typical values they assume. Note there is a distinction between single response calls for service (i.e., those calls for which only one two-officer car will respond) and multiple response calls for service (i.e., those calls for which one one-officer car and one two-officer car will respond).

2.2 Illustrative Model Runs

Since a major objective of any analysis involving alternative deployment strategies is to compare its performance to the current, or "status quo", performance, it is necessary to specify the current performance. It should be noted that while the mixed-mode model is prescriptive, a status quo model is necessarily descriptive (i.e., a performance level is computed based on the assigned manpower). Finally, recall that the status quo operating procedures include exclusive use of two-officer cars and that these cars only respond to calls for service that originate in their precinct (i.e., there is no interprecinct dispatching).

Using a standard multi-server queueing model, performance measures were computed for the status quo allocations strategy (see the top row of Figure 2.) City-wide, 444 patrol officers are assigned to 222 patrol cars, reflecting the fact that only two-officer cars are used. The average fraction of high and low priority calls that are queued is equal to 0.19. (For the sake of brevity, only city-wide averages are listed). This implies that all cars are simultaneously busy about one-fifth of the time. The average response time to high priority calls is 5.3 minutes and a two-officer car on the average is busy answering calls for service 42 percent of the time. Finally, the average patrol frequency is 0.19 passes per hour (i.e, 1.5 passes during an eight hour shift). These values will serve as the basis for comparing the status quo and the mixed-mode allocation strategies.

Figure 1

Inputs for Mixed-Mode Model

	Typical Values
- Average service time on single response calls for service	25.0 minutes
- Average service time on multiple response calls for service	22.0 minutes
- Average call for service rate of single response calls for service	1.0 calls/hour
- Average call for service rate of multiple response calls for service	0.5 calls/hour
- Average number of patrol cars responding to multiple response calls for service	2.5 cars
- Response speed of patrol cars	12.0 mph
- Patrol speed of patrol cars	8.0 mph
- Area of precinct	2.0 sq. miles
- Patrollable street miles of precinct	40.0 miles
- Model to fielded patrol car conversion factor	0.67

Figure 2

Constant Performance Comparison

Allocation Mode	Constraints Satisfied	Manpower	# Two-Officer Cars	# One-Officer Cars	Fraction High Priority Calls Queued	Fraction Low Priority Calls Queued	High Priority Response Time	Two-Officer Car Utilization	One-Officer Car Utilization	Fraction Inter-Precinct Dispatch	Fraction of Time Outside 'Home' Precinct	Patrol Frequency (passes/hr)
Status Quo	-	444	222	0	0.19	0.19	5.3	0.42	-	0.0	0.0	0.19
Mixed Mode	High Priority Response Time	279	88	103	0.08	0.57	5.3	0.32	0.69	0.30	0.10	0.14
	High Priority Response Time, Probability Low Priority Call Queued	345	88	169	0.08	0.19	5.3	0.32	0.42	0.30	0.10	0.23

Constant Performance Comparisons

There are many ways to compare performances of two allocation strategies. The approach discussed below involves a "constant performance" comparison, wherein the key question is "what manpower level would be required under the mixed-mode strategy to equal the status quo performance?" However, this goal needs further clarification since it is unclear what exactly "equal performance" means. To gain insight into this question, imagine allocating patrol cars one-by-one to each precinct under the mixed-mode strategy. As more cars are allocated the different performance measures improve (e.g., response time decreases, patrol frequency increases, etc.). At some point, after allocating a given number of cars, one of the mixed-mode performance measures, say high priority response time, will become equal to the status quo high priority response time value. (All of the other mixed-mode performance measures are worse than the corresponding status quo values at this point). A second mixed-mode performance measure, say the fraction of low priority calls queued, will become equal to its corresponding status quo value after a few more cars are allocated. Eventually, as more cars are allocated, all the mixed-mode performance measures will become equal to or exceed their status quo counterpart. With this background, the question remains, at what point is the mixed-mode performance equal to the status quo performance?

The second column in Figure 2, which displays the results of the "constant performance" mixed-mode and status quo comparison, delineates what is meant by constant performance in these illustrative runs. In the first row below the status quo performance line, high priority response time is listed as the "constraint satisfied". Thus, the assumption here is that we are only concerned with the high priority response time; if only the high priority response time under the mixed-mode strategy is equal to the status quo high priority response time, then that constitutes "constant performance". The 279 officers, which are allocated in 88 two-officer cars and 103 one-officer cars, respond to high priority calls in 5.3 minutes, which is equal to the high priority response time reached by the 222 two-officer cars under the status quo strategy.

While the high priority response times are equal, some of the other performance measures are worse than the corresponding status quo values. The fraction of low priority calls queued (.57), the one-officer car utilization level (69 percent), and patrol frequency (0.14 passes per hour) are all worse than the status quo levels at the 279-officer manpower level. To remedy this situation, the planner may wish to allocate more one-officer cars. The second mixed-mode run displayed in Figure 2, in fact, satisfies both the high priority response time and fraction of low priority calls that are queued constraints. Notice that an additional 66 one-officer cars (i.e., an increase from 103 to 169) were needed to reduce the value of the fraction of low priority calls that are queued to 0.19, the status quo level. (High priority response time did not decrease as a result of increasing the number of one-officer cars because two-officer cars, whose number was not increased, provide the initial response to high priority calls). The additional 66 one-officer cars also reduced the one-officer car workload to 42 percent, which is equal to the status quo level, and increased patrol frequency to 0.23 passes per hour, a level higher than the status quo value.

In sum, it is evident that the mixed-mode strategy can provide this city with comparable performance at greatly reduced manpower levels. While high priority calls are adequately handled with 279 officers, the workload of the one-officers and thus their ability to respond quickly to low priority calls and to provide prompt backup to two-officer cars on high priority calls at this manning level is most likely unacceptable. The police planner would most likely opt for the 345 manning level as the acceptable constant performance manning level. This manning level represents a 22.3 percent reduction in patrol officer staffing. Since over 90 percent of the budget of an urban police department is consumed by labor costs, the mixed-mode deployment strategy can realize significant cost savings for the city.

Constant Manpower

In this section, a different type of comparison is made. Instead of keeping performance constant, manpower is held constant in order to see by what margin performance can be improved under the mixed-mode strategy. This illustrates yet another capability of the model.

Figure 3 displays the results of the constant manpower runs. Again, the status quo performance measures are listed in the top row. The first mixed-mode row in the Figure is a constant manpower production run in which emphasis is placed on high priority response time. In this instance the 444 officers will be placed in 171 two-officer cars and 102 one-officer cars. Notice that the high priority response time is quite low (3.0 minutes), but the fraction of low priority calls that are queued and the one-officer car utilization are both larger than the status quo level. By re-distributing the 444 officer into 138 two-officer cars and 168 one-officer cars, the fraction of low priority calls that are queued and the one-officer car utilization are no worse than the status quo level. At the same time, the high priority response time has risen from 3.0 to 3.6 minutes, still well below the status quo level.

Other Performance Comparisons

In the example above, just two possible changes were considered -- constant performance and constant manpower changes. Obviously, other changes are possible. For example, one could obtain some "intermediate point" by

Figure 3

Constant Manpower Comparison

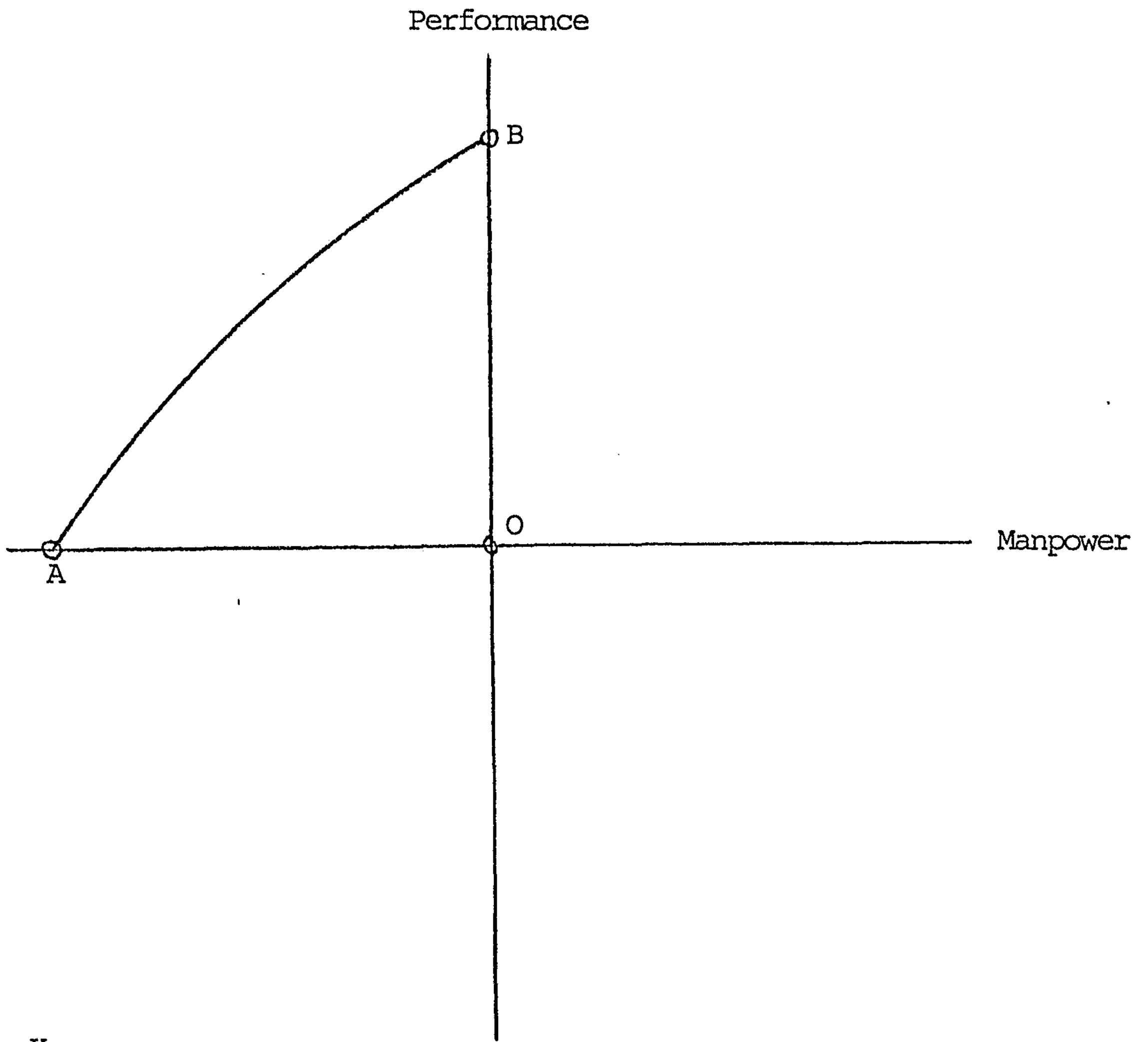
Allocation Mode	Constraints Satisfied	Manpower	# Two-Officer Cars	# One-Officer Cars	Fraction High Priority Calls Queued	Fraction Low Priority Calls Queued	High Priority Response Time	Two-Officer Car Utilization	One-Officer Car Utilization	Fraction Inter-Precinct Dispatch	Fraction of Time Outside 'Home' Precinct	Patrol Frequency (passes/hr)
Status Quo	-	444	222	0	0.19	0.19	5.3	0.42	-	0.0	0.0	0.19
Mixed Mode	High Priority Response Time	444	171	102	0.01	0.57	3.0	0.17	0.69	0.07	0.01	0.26
	High Priority Response Time, Probability Low Priority Call Queued	444	138	168	0.02	0.19	3.6	0.20	0.42	0.11	0.02	0.30

increasing performance by an amount not as great as in the constant manpower example and reducing manpower by an amount less than in the constant performance example. These and other possible mixed-mode operating points are depicted in Figure 4. The origin of the graph (i.e., point O) represents the status quo operating point, with manpower on the X axis and performance on the Y axis. The positive (negative) X axis denotes increased (decreased) manpower compared to the status quo level. Similarly, the positive (negative) Y axis denotes increased (decreased) performance compared to the status quo level. Noticed that the constant performance example describes an operating point on the X axis to the left of the origin (i.e., point A), while the constant manpower example describes an operating point on the Y axis, above the origin (i.e., at point B). Clearly, the model could be used to examine operating points in the northeast quadrant of the graph, where both manpower and performance are increased. Points below the X axis represent a performance level worse that the status quo level and most likely would not be considered in the analysis.

The curve linking points A and B on the graph depict the performance to be achieved at various levels of manpower under the mixed-mode strategy. As expected, the curve has a positive slope, indicating that as manpower increases, performance also increases. Also implicit in the curves in the concept of "dimishing returns" from marginal increase in patrol staffing, which explains the concave shape of the curve. This curve would allow city planners, police officials, and other interested parties, in effect, to select the operating point desired under the mixed-mode allocation strategy. If current, or close to current, manpower levels are to be maintained, then the graph quickly reveals the expected performance gains. Similarly, if severe budget cutbacks — including manpower cutbacks —are to be imposed, the effect

Figure 4

Performance Versus Manpower Graph



Key:

O = Status Quo Operating Point

A = Constant Performance Operating Point

B = Constant Manpower Operating Point

on mixed-mode performance of these cutbacks can be quickly determined.

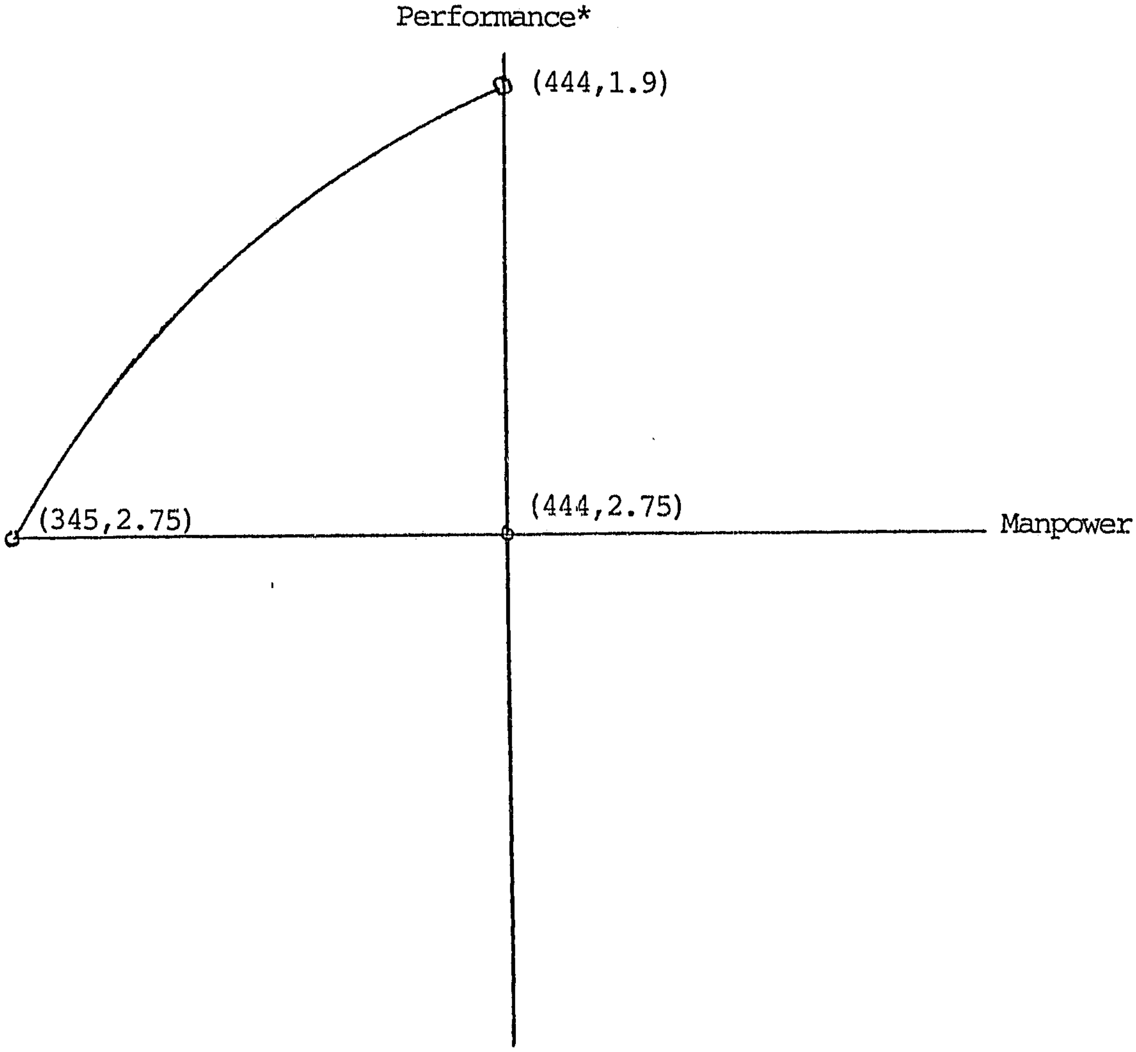
To be more useful, however, the precise meaning of performance, the Y axis in Figure 4 must be clarified. In general, any one, or combination of the model-computed performance measures could be used. If more than one performance measure is to be included on the performance scale, then some type of weighted average could be used. We illustrate the use of such a scheme in Figure 5, where performance is defined to be the arithmetic average of high priority response time and the fraction of low priority calls queued. Of course, this particular performance index selection is just an illustration; in practice, however, the selection of performance measures to be used as the basis for constructing the performance versus manpower graphs is extremely important. For example, the police patrolman's union may refuse to even consider the new strategy unless the number of one-officer cars — which they may be much opposed to — is included in the definition of performance. By using mathematical models such as the ones described in this section, the consequences of alternative definitions of performance can be assessed.

Summary

In this Section, a model was discussed that is designed to reflect a particular set of mixed-mode operating characteristics. Specific roles for the one-officer and two-officer cars are defined and modelled. Also, the Section focused on two particular types of comparative runs, namely the constant performance and the constant manpower comparisons. However, because of the flexibility of the model, it can easily to modified to reflect different mixed-mode characteristics, such as different backup policies, different response areas, and other one-officer car-specific or two-officer car-specific constraints. This feature of the model is critical since there are so many different variations of mixed-mode patrol. Inasmuch as mixed-mode

Figure 5

Performance Versus Manpower: An Example



* Performance = ½(High Priority Response Time + Probability a Low Priority Call is Queued)

patrol presents new challenges to police planners, mathematical models are indeed a valuable resource.

3 CASE STUDY: DISAGGREGATE MODELS

Aggregate police patrol models, discussed in Section 2, provide powerful tools to city and police planners. Questions relating to city-wide or precinct-wide deployment strategies or, in general, questions relating to the temporal allocation of one- and two-officer cars can be addressed with aggregate models. However, because of the underlying limitations of the aggregate models' mathematical assumptions, namely that all cars of a certain type (e.g., two-officer or one-officer cars) in a particular precinct are identical in terms of workload, patrolled area, and other characteristics the aggregate models cannot address more specific and detailed patrol deployment questions, especially those concerning the spatial allocation of patrol cars. For example, a police planner — faced with deploying both one- and two-officer cars — must decide what patrol beats should be one-officer car beats and which should be two-officer car beats. Area characteristics such as the types of calls for service (i.e., the precentage of high versus low priority calls) received, demographics, and the proximity of backup units must be considered. In addition, car-specific dispatching procedures (such as backup policies) must also be modified to reflect the necessity of ensuring the safety of the officers in one-officer cars. For example, the planner may wish to restrict a one-officer cars' area of response to, say, its beat and only one other beat. These types of questions are best addressed by using "disaggregate" models, models that consider both a finer-grained structure of the city and individual patrol car characteristics.

An example of a disaggregate model is the Hypercube queueing model, a model that has been in the public domain since 1975 and is used to study the behavior of multi-server queueing systems with distinguishable servers .[6]

Below, Hypercube runs are discussed that illustrate both some of the issues in one- and two-officer patrol car deployment strategies and the capabilities of Hypercube in addressing those issues.

3.1 Model Description

The structure and assumptions of Hypercube are well-documented in other sources.[7] Our main purpose in this section, therefore, is to discuss the salient differences in Hypercube and the Mixed-Mode models, in particular, and disaggregate models and aggregate models, in general, that are important in the study of one- and two-officer patrol car allocation strategies.

Area Geography

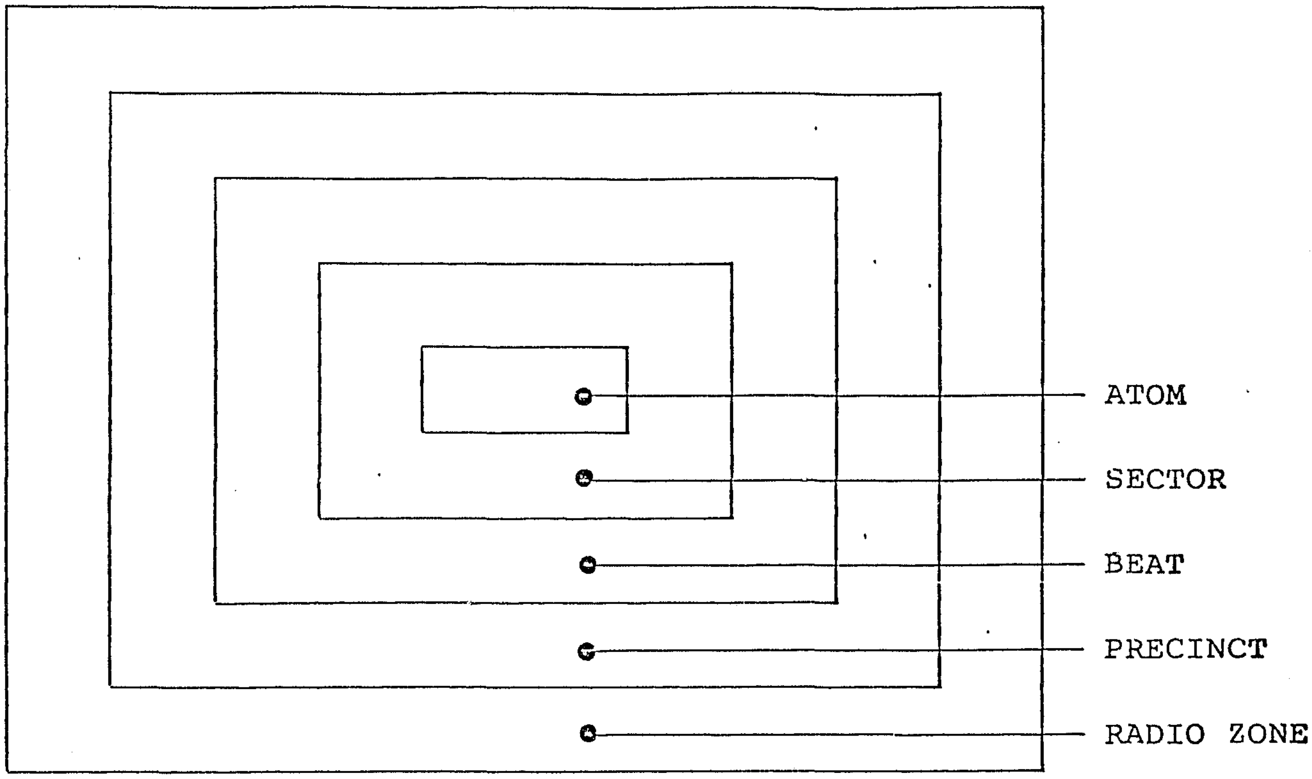
In the illustrative aggregate model runs in Section 2, the city was partitioned into precincts, areas in which several cars —typically at least four and sometimes as many as ten — patrol and respond to calls for service. The precinct is the smallest unit of area considered and for which performance measures are computed. The Hypercube model allows for a much finer-grained partitioning of the response area. As shown in Figure 6, three geographic units smaller than the precinct can be investigated: a beat, a sector, and a reporting area. Reporting areas, the smallest geographic unit, are typically four to eight city blocks. The Hypercube requires that reporting area-specific geography (i.e., location relative to the other reporting areas, the area in square miles and the number of street miles) be specified.

Patrol Car Characteristics

Recall that two important assumptions in the mixed-mode models are that all one-officer patrol cars in a precinct are "identical" and all two-officer cars within a precinct are "identical" (i.e., all one-officer cars within a precinct have approximately equal utilization levels and patrol approximately equal numbers of square miles, and, similarly, all two-officer cars within a

Figure 6

Partitioning of Geographic Units



precinct have approximately equal utilization levels and patrol approximately equal numbers of square miles). The Hypercube model, on the other hand, does not make this simplification and considers the identity and characteristics of each individual patrol car. This includes defining the area of patrol and area of response, an important capability when deploying a combination of one-officer and two-officer car. Additionally, the desired dispatching algorithm can be car-specific. Thus, one-officer cars, for example, can be dispatched only to calls originating from certain reporting areas. More generally, Hypercube allows the planner to specify the order in which cars are to be dispatched for calls originating from any reporting area. The ability to define selective roles at this level of detail for one-officer cars, as well for two-officer cars, is indeed a powerful and useful capability.

Performance Measures

Not surprisingly, whereas the aggregate models computed precinct-level performance measures, Hypercube can compute beat, sector, and reporting area performance measures (see Figure 7). Again, this is useful in monitoring and controlling the patrol and response activities of one-officer cars. The police planner, for example, may want to restrict one-officer car activities in certain areas, in which case he/she would monitor the fraction of calls for service generated from, say, a high crime area, that are handled by the one-officer car. If the fraction is unacceptably high, the planner would redefine the deployment strategy.

3.2 Illustrative Runs

The illustrative runs in this section focus on patrol cars in the precinct pictured in Figure 8. For the purposes of these analyses, the precinct was partitioned into 21 reporting areas. The total area of the district being only a few square miles, most of the reporting areas are

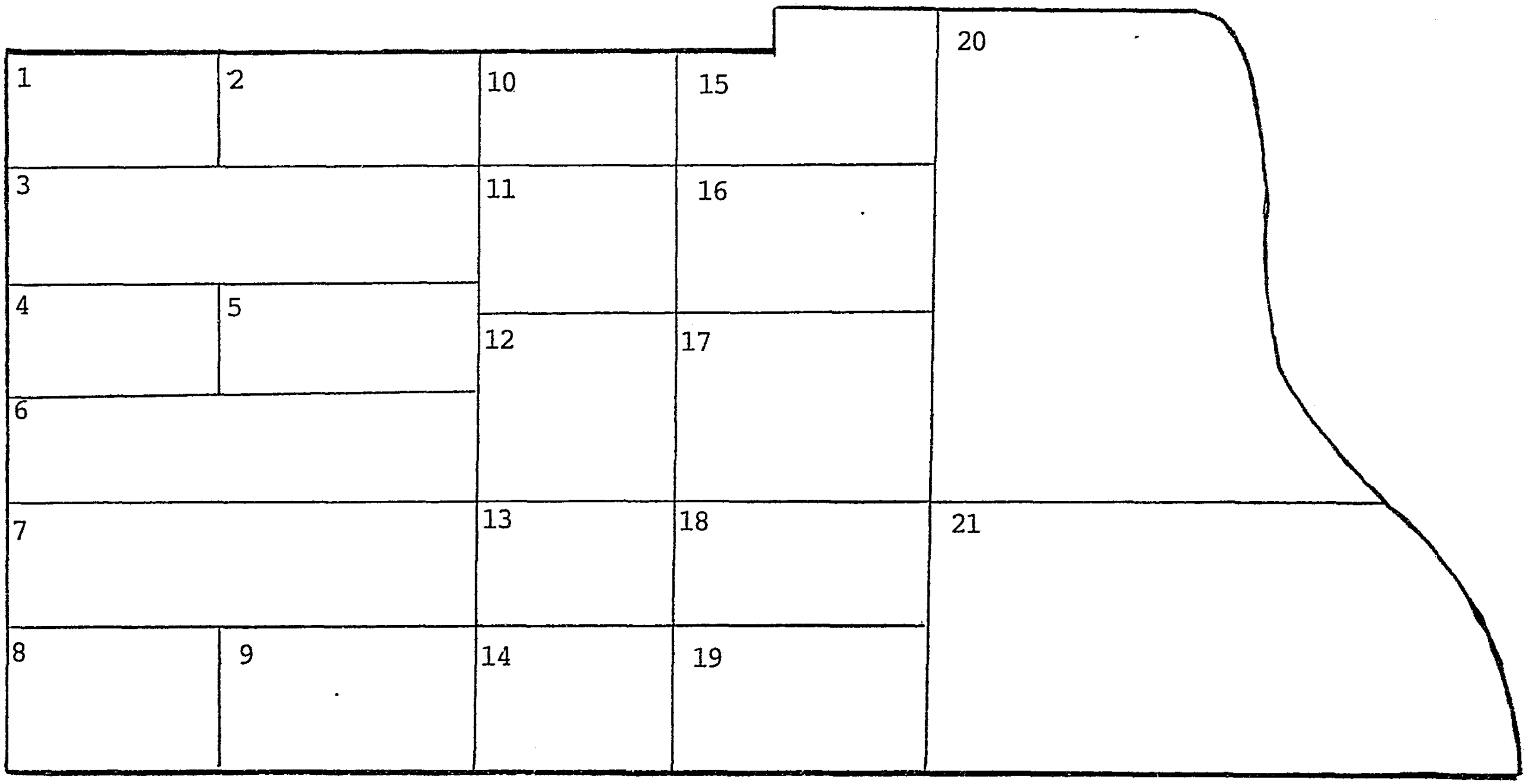
Figure 7

Hypercube Performance Measures

- Precinct-wide mean travel time
- Precinct-wide workload and workload imbalance
- Precinct-wide fraction of dispatches that remove a patrol car from its beat
- Precinct-wide fraction of calls answered by backup patrol cars
- Workload of each patrol car (measured in fraction of time busy servicing calls for service)
- Mean travel time to each reporting area
- Mean travel time of each patrol car
- Fraction of responses in each patrol car's beat that are handled by other patrol cars
- Fraction of responses of each patrol car that dispatch the car outside of its beat
- Fraction of responses within each reporting area that are handled by each of the patrol cars

Figure 8

Precinct Map with Reporting Areas



roughly ten city blocks. Reporting areas 20 and 21 are, however, much larger. Currently, the police department deploys four two-officer cars in the precinct. Each car's primary response area, or beat, is roughly one fourth of the precinct, but inter-beat dispatches are routine. Interprecinct dispatches, however, are rare and occur only in extenuating circumstances.

Due to budget cutbacks, the department is considering using one-officer cars on a limited basis, with this particular precinct being the site of an initial pilot feasibility test. Specifically, two proposals are to be investigated in detail. The first proposal involves replacing one of the two-officer cars with a one-officer car, which will be used primarily for preventive patrol purposes throughout the precinct. The one-officer car would respond to calls for service only if the three two-officer cars are simultaneously busy on other calls for service. The second proposal being considered is identical to the first, except there would be two "rover" one-officer cars instead of just one. In this second proposal, the total number of patrol officers in the precinct is held constant. As in the first proposal, if all (three) two-officer cars are simultaneously busy, then one of the rover cars would be assigned the call (they would alternate handling the calls).

Model Assumptions

We will briefly state the important model assumptions used in the Hypercube runs discussed below. The total precinct wide call for service rate is assumed to be 4.1 calls per hour; the call rate within each reporting area is proportional to the area of that reporting area. The average service time of the two-officer cars is 27.5 minutes, while that of the one-officer cars is 30.0 minutes, reflecting the savings in service time when two officers are present at the scene. All cars travel at 12 miles per hour. Finally, one car is dispatched to each call for service. The closest — in a probabilistic sense — two-officer car is dispatched, if one is available. If all the cars are busy, including the one-officer rover cars, the call is queued and assigned to the first available unit.

A Status Quo Run

For comparison purposes, a status quo Hypercube run (i.e., a run assuming the current, four two-officer car, deployment strategy is in effect) was performed. In this run it was assumed that (refer to Figure 8) car number 1, Ida, patrols reporting areas 1,2,3,5,10,11, car number 2, George, patrols reporting areas 4,6,7,8,9,12,13,14, car number 3, Boy, patrols reporting areas 15,16,and 20, and car number 4, Charles, patrols reporting areas 17,18,19, and 21. The results of the run are summarized in Figure 9. Notice that each of the four two-officer cars have approximately equal workload (from a low of 42.9 percent for car Ida to a high of 49.7 percent for car Boy). Not surprisingly, a significant percentage of each car's dispatches are to calls for service originating outside of that car's beat. For example, 50.9 percent of car Ida's dispatches are out of Ida's beat. Finally, it should be noted that the average precinct-wide travel time is 2.39 minutes.

One One-Officer Rover Car

In this run, the district was partitioned so that the beat of each of the three two-officer cars is roughly one third the precinct (Ida was assigned reporting areas 1 to 9, George was assigned reporting areas 10 to 19, and Boy was assigned reporting areas 20 and 21). Car Charles, the one-officer rover car, patrols the entire district and only respond to calls for service if all three two-officer cars are simultaneously busy.

The results of this run are displayed in Figure 10. While the workload of the two-officer cars has increased anywhere from five to ten percent over the status quo workload levels, the workload levels of the two-officer cars under

Figure 9

Status Quo Hypercube Run

RMP SECTOR CARS ...TOTAL NUMBER OF = 4
ATOMS ...TOTAL NUMBER OF = 21
AVERAGE SERVICE TIME= 27.50 MINUTES
AVERAGE NUMBER PER HOUR OF CALLS FOR SERVICE = 4.060
AVERAGE NUMBER PER 27.50 MINUTES OF CALLS FOR SERVICE = 1.861
AVERAGE UTILIZATION FACTOR
(IN THE CASE OF UNLIMITED LINE CAPACITY)= 0.465

PRECINCT-WIDE AVERAGE TRAVEL TIME= 2.385 MINUTES

AVERAGE TRAVEL TIME FOR QUEUED CALLS= 3.275 MINUTES
PROBABILITY OF SATURATION= 0.14154
PRECINCT-WIDE AVERAGE WORKLOAD (% TIME BUSY)= 0.46521
STANDARD DEVIATION OF WORKLOAD= 0.028
MAXIMUM WORKLOAD IMBALANCE= 0.06800

FRACTION OF DISPATCHES THAT ARE INTER-BEAT = 0.46044

PERFORMANCE MEASURES THAT ARE SPECIFIC TO EACH SECTOR CAR

ID OF SECTOR CAR NAME	NO	WORKLOAD OF CAR	% OF MEAN	FRACTION OF DISPATCHES OUT OF BEAT	% OF MEAN	AVERAGE TRAVEL TIME
IDA	1	0.429	92.3	.5092	110.6	2.700
GEORGE	2	0.461	99.1	.4358	94.7	2.365
BOY	3	0.497	106.9	.4572	99.3	2.210
CHARLES	4	0.473	101.7	.4438	96.4	2.306

PERFORMANCE MEASURES THAT ARE SPECIFIC TO EACH BEAT

ID OF BEAT NAME	NO	WORKLOAD OF BEAT	% OF MEAN	FRACTION OF DISPATCHES INTER-BEAT	% OF MEAN	AVERAGE TRAVEL TIME
F,H,I	1	0.435	93.5	.5195	112.8	2.459
E,G,H	2	0.452	97.2	.4261	92.5	2.422
B,D	3	0.504	108.4	.4614	100.2	2.331
A,C	4	0.470	100.9	.4376	95.0	2.338

Figure 10

One-Rover Car Hypercube Run

RESPONSE_UNIT ...TOTAL NUMBER OF = 4
ATOM ...TOTAL NUMBER OF = 21
AVERAGE SERVICE TIME= 28.09 MINUTES
AVERAGE NUMBER PER HOUR OF CALLS FOR SERVICE = 4.060
AVERAGE NUMBER PER 28.09 MINUTES OF CALLS FOR SERVICE = 1.900
AVERAGE UTILIZATION FACTOR
(IN THE CASE OF UNLIMITED LINE CAPACITY)= 0.475

REGION-WIDE AVERAGE TRAVEL TIME= 2.758 MINUTES

AVERAGE TRAVEL TIME FOR QUEUED CALLS= 3.275 MINUTES
PROBABILITY OF SATURATION= 0.15038
REGION-WIDE AVERAGE WORKLOAD (% TIME BUSY)= 0.47197
STANDARD DEVIATION OF WORKLOAD= 0.136
MAXIMUM WORKLOAD IMBALANCE= 0.29526

FRACTION OF DISPATCHES THAT ARE INTER-DISTRICT = 0.36798

PERFORMANCE MEASURES THAT ARE SPECIFIC TO EACH SECTOR CAR

ID OF SECTOR CAR NAME	NO	WORKLOAD OF UNIT	% OF MEAN	FRACTION OF DISPATCHES OUT OF BEAT	% OF MEAN	AVERAGE TRAVEL TIME
IDA	1	0.508	107.7	.4537	123.3	2.792
GEORGE	2	0.567	120.1	.4477	121.7	2.654
BOY	3	0.541	114.6	.3731	101.4	2.572
CHARLES	4	0.272	57.6	.0176	4.8	3.275

PERFORMANCE MEASURES THAT ARE SPECIFIC TO EACH BEAT

ID OF BEAT NAME	NO	WORKLOAD OF BEAT	% OF MEAN	FRACTION OF DISPATCHES INTER-BEAT	% OF MEAN	AVERAGE TRAVEL TIME
IDA	1	0.533	112.1	.3369	91.6	2.842
GEORGE	2	0.675	142.1	.3952	107.4	2.577
BOY	3	0.693	145.8	.3692	100.3	2.853
CHARLES	4	1.900	400.0	.3694	100.4	2.752

this one-rover car strategy are not unacceptably high. The one-officer car, Charles, is only used to a limited extent — it has a workload level equal to 27.2 percent —as the police planner had intended. Car Charles's average travel time to calls for service that it handles is higher than the other cars (3.28 minutes versus an average of roughly 2.6 minutes for the two-officer cars), reflecting the fact that Charles patrols the entire precinct. The precinct-wide effect of the one-rover car strategy can also be measured by comparing the precinct-wide performance measures in Figures 9 and 10. In terms of average travel time to calls for service and the probability that a call for service will be delayed in the dispatcher's queue, the system performance level does not appear to have suffered significant adverse effects (the former performance measure increased less than half a minute and the latter increased only about one percent). The maximum workload imbalance, an important issue to patrol officers, did, however, increase from 6.8 percent to 29.5 percent, an increase that was totally expected given the nature of the one-rover car strategy.

Two One-Officer Rover Cars

Instead of deploying just one rover car, the planner also wishes to examine the consequences of using two rover cars, thus maintaining a constant level of manpower (i.e., instead of four two-officer cars, three two-officer cars and two one-officer cars are deployed). In terms of ensuring the safety of the officer in the one-officer cars, the extra rover car will most certainly further decrease the number of calls for service to which each one-officer cars must respond. In this Hypercube run, each of the three two-officer cars is assigned to the same reporting areas as in the one rover car run. Both one-officer cars will patrol the entire precinct and respond to calls for service only if all the two-officer cars are busy.

Figure 11 summarizes the results of the run. As the planner had intended, the average workload of the one-officer cars has decreased, from 27.2 percent under the one rover car strategy, to 17.8 percent under the two rover car strategy. Thus, the one-officer cars spend over 80 percent of the in-service time on preventive patrol. At the same time, the workload of the two-officer cars has decreased slightly. More important, however, is the overall effect of the additional one-officer car on precinct-wide performance. The probability that an incoming call will be delayed in the dispatcher's queue has decreased by roughly two thirds, from 15.0 percent to 5.2 percent. Average travel times have also decreased slightly from the value under the one-rover car strategy, but are still higher than the status quo value.

Summary

Even for those departments using only two-officer cars, spatially allocating police cars presents many problems. The planner must address such issues as workload imbalances, neighborhood inequities in accessibility to police services, intensity of preventive patrol in high crime areas, and the overall precinct-wide performance. However, for those departments employing a mixed-mode allocation strategy, spatial deployment issues become even more complex. Questions such as in which beats is it appropriate for one-officer cars to patrol, in which beats is it appropriate for one-officer cars to respond to calls for service, the proximity of two-officer backup cars, and, in general, how to deploy two different types of resources make mathematical modelling even more essential. As demonstrated in this Section, the Hypercube model can be a valuable aid to police planners faced with these difficult issues.

Figure 11

Two-Rover Car Hypercube Run

```
RESPONSE_UNIT        ...TOTAL NUMBER OF =  5
ATOM       ...TOTAL NUMBER OF =  21
AVERAGE SERVICE TIME=  28.45 MINUTES
AVERAGE NUMBER PER HOUR OF CALLS FOR SERVICE  =   4.060
AVERAGE NUMBER PER  28.45 MINUTES OF CALLS FOR SERVICE  =    1.925
AVERAGE UTILIZATION FACTOR
   (IN THE CASE OF UNLIMITED LINE CAPACITY)=  0.385
```

REGION-WIDE AVERAGE TRAVEL TIME=   2.728 MINUTES

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AVERAGE TRAVEL TIME FOR QUEUED CALLS=   3.275 MINUTES
PROBABILITY OF SATURATION= 0.05193
REGION-WIDE AVERAGE WORKLOAD (% TIME BUSY)= 0.37880
STANDARD DEVIATION OF WORKLOAD=   0.185
MAXIMUM WORKLOAD IMBALANCE= 0.36518
```

FRACTION OF DISPATCHES THAT ARE INTER-BEAT = 0.32923

PERFORMANCE MEASURES THAT ARE SPECIFIC TO EACH SECTOR CAR

ID OF SECTOR CAR NAME	NO	WORKLOAD OF UNIT	% OF MEAN	FRACTION OF DISPATCHES OUT OF BEAT	% OF MEAN	AVERAGE TRAVEL TIME
IDA	1	0.481	127.0	.4241	128.8	2.737
GEORGE	2	0.543	143.3	.4285	130.1	2.592
BOY	3	0.515	136.0	.3460	105.1	2.498
CHARLES	4	0.178	46.9	.0061	1.9	3.275
FRANK	5	0.178	46.9	.0061	1.9	3.275

PERFORMANCE MEASURES THAT ARE SPECIFIC TO EACH BEAT

ID OF BEAT NAME	NO	WORKLOAD OF BEAT	% OF MEAN	FRACTION OF DISPATCHES INTER-BEAT	% OF MEAN	AVERAGE TRAVEL TIME
IDA	1	0.540	140.2	.2962	90.0	2.794
GEORGE	2	0.684	177.6	.3577	108.6	2.560
BOY	3	0.702	182.2	.3303	100.3	2.827
CHARLES	4	1.925	500.0	.3304	100.4	2.723
FRANK	5	1.925	500.0	.3304	100.4	2.723

NOTES

1. "National Survey of Police Departments Utilizing Both One- and Two-Officer Cars", Public Systems Evaluation, Inc., 1983.

2. See, for example,
   L. Green and P. Kolesar, "The Feasibility of One-Officer Patrol in New York City", Management Science, Vol. 30, pp. 963-981, 1984.
   L. Green and P. Kolesar, "A Comparison of the Multiple Dispatch and M/M/C Priority Queueing Models of Police Patrol", Management Science, Vol. 30, pp. 665-670, 1984.
   K.R. Chelst, "Deployment of One- Vs. Two-Officer Patrol Units: A Comparison of Travel Times", Management Science, Vol. 27, pp. 213-230.

3. J.M. Chaiken and P. Dormont, "Patrol Car Allocation Model: User's Manuel", R-1786/2-HUD/DOJ, The Rand Corp., 1975.
   J.M. Chaiken and P. Dormont, "A Patrol Car Allocation Model: Capabilities and Algorithms", Management Science, Vol. 24, pp. 1291-1300, 1978.

4. E.H. Kaplan, "Evaluating the Effectiveness of One-Officer Versus Two-Officer Patrol Units", Journal of Criminal Justice, Vol. 7, pp. 325-355, 1979.

5. "One- Versus Two-Officer Police Cars: An Overview of Attitudes and Implementation Experiences", Public Systems Evaulation, Inc., 1985.

6. R.C. Larson (ed.), Police Deployment: New Tools for Planners, Lexington Books, Lexington, MA, 1978.

7. See Note 6 or,
   R.C. Larson, "A Hypercube Queueing Model for Facility Location and Redistricting in Urban Emergency Services," Computers and Operations Research, Vol.1, pp. 67-95, 1974.